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Engineered Band Structure in Micromachined Quantum Wells

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Introduction: The ability to engineer the optical and electronic properties of epitaxially grown compound semiconductor heterostructures in the *growth* (vertical) direction has enabled the explosive growth and success of semiconductor lasers, photodetectors, and modulators. However, high-quality *laterally* patterned band structure in these materials has proven much more elusive. Materials with precise lateral band structure control are of particular importance for applications in integrated photonics and artificial quantum confined systems. In addition, the ability to engineer birefringence in the plane of the semiconductor heterostructure has important implications for electro-optic polarization modulators and for birefringent phase-matching in nonlinear frequency conversion.

We describe how micromachining semiconductor heterostructures into suspended structures partially detached from the substrate can be used not only to laterally pattern band structure but also to provide a better understanding of the interaction between strain, band structure, and optical absorption in these materials. Suspended quantum wells grown with strain provide a direct comparison of two sets of strain components in the same sample. Thus, by carefully comparing the optical properties of an as-grown area with a suspended area, important photonic, electronic, and mechanical properties of these microstructures can be discerned. Knowledge of these properties can then

be used to design future-generation micromachined and nanomachined semiconductor heterostructures. Our work also shows that compound semiconductor-based microelectromechanical systems (MEMS) are potential replacements for some silicon-based MEMS due to their greater material flexibility and control over strain.¹⁻³

Micromachining Quantum Wells: The epitaxially grown semiconductor heterostructures studied in this work are $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ (lattice-matched) multiple quantum wells (MQW's) with either InAlAs or InGaAlAs strained barriers. The MQW is grown on a $1.5\text{-}\mu\text{m}$ thick InAlAs or InP sacrificial layer, which itself is grown on an InGaAs etch stop layer on the InP substrate. Standard photolithography and a nonselective wet etch are used to pattern the MQW into mesas. A timed $\text{HCl}:\text{H}_3\text{PO}_4$ (1:1) selective etch is then used to etch the sacrificial layer both where it had been exposed as well as partially underneath the MQW, thereby releasing the MQW from the substrate. These suspended MQW's can be fabricated into various shapes, including microbridges, microcantilevers, or micropedestals.

Band Structure Deformation: MQW's with strained barriers that are released from the substrate produce strain in the QW layers as the strain in the barriers partially relaxes. Thus, the strain tensor in a suspended quantum well is markedly different than the strain tensor in the unreleased (as-grown) areas of the quantum well (Fig. 7). This postgrowth strain engineering leads to in-plane band structure engineering: strain in semiconductors couples to band structure through the deformation potentials. The coupling is a function of the components of the strain tensor and the crystal symmetry of the semiconductor and can be measured using polarization-specific optical absorption spectroscopy. Simply put, net compressive strain in the quantum well leads to a blue shift of the band gap and

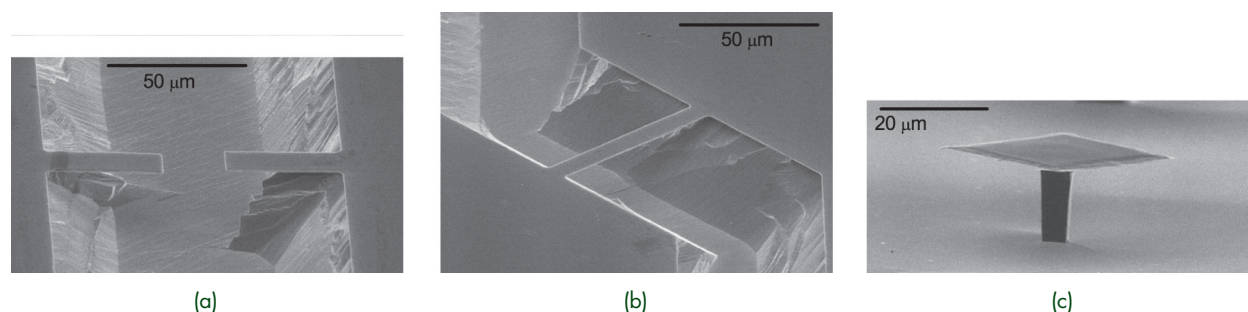


FIGURE 7

Micromachined quantum wells patterned as (a) microcantilevers, (b) microbridges, and (c) micropedestals. In each case, the suspended membrane is a multiple InGaAs quantum well that is about 400-nm thick with tensile barriers.

net tensile strain leads to a red shift. In addition, an anisotropy of the in-plane strain components in the quantum well leads to an optical absorption anisotropy between the two orthogonal linear polarizations.

Figure 8 shows an example of laterally engineering band structure in a MQW with tensile barriers. The MQW forms the top of a micropedestal such that the central portion (the dark rectangle in the inset of Fig. 8(a)) is still attached to the sacrificial layer, while the outer portion is freely suspended above the substrate. Partial strain relaxation in the barriers of the suspended areas leads to a net compressive strain in the quantum well layers. Thus, the band gap in the quantum well is expected to be bluer in the suspended area than in the central area that is still attached. Figure 8(b) shows the optically mapped heavy-hole band gap across the surface of the micropedestal, confirming this expectation. A 9 meV band gap shift results from a sample grown with an initial barrier strain of 0.69% and is in excellent agreement with our band structure models.

Figure 9 shows band structure deformation along a microbridge in two different samples. A microbridge differs from a micropedestal or a microcantilever in that the barrier strain component in the direction parallel to the bridge length cannot relax, but the components perpendicular to the bridge length are free to relax. Thus, the in-plane strain components in the quantum well are anisotropic, leading to anisotropic optical absorption and therefore birefringence. The differential transmission spectra in Fig. 9 are a measure of the optical absorption at a given wavelength. In Fig. 9(a), an initial tensile barrier strain induces anisotropic compressive strain in the quantum well. This leads to a blue-shift and decreased (increased) absorption at the heavy (light) hole for light polarized parallel to

the microbridge. In Fig. 9(b), an initial compressive barrier strain induces anisotropic tensile strain in the quantum well. This leads to a red-shift and increased (decreased) absorption at the heavy (light) hole for light polarized parallel to the microbridge. Thus, micro-machined microbridges lead not only to a shifted band gap but also to a modification of the band structure symmetry, from one that is isotropic in the growth plane to one that is highly anisotropic. The measured optical absorption spectra in Fig. 9 are also in excellent agreement with our band structure models.

Summary: This demonstration of controlled three-dimensional band-structure patterning represents the beginning of a wide range of new research avenues based on the combination of micromachining, MEMS, and optically active III-V semiconductors. Potential applications include arrays of surface-normal modulators, optically active piezoelectric materials, quasi-phase matching in waveguides, and directly patterned quantum-dot arrays.

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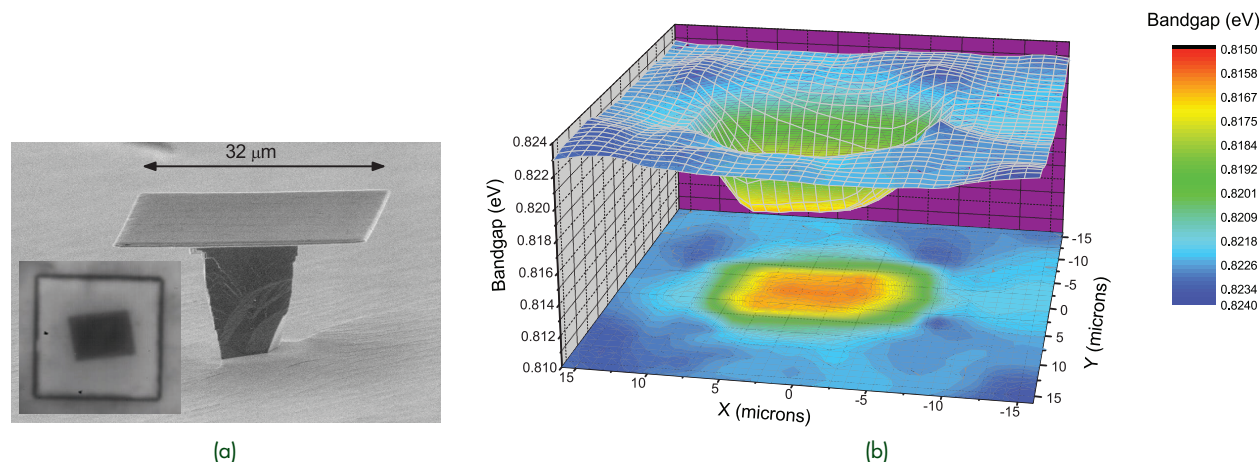


FIGURE 8

Band structure deformation in a quantum well micropedestal. Strain relaxation in the suspended area of the quantum well results in a blue-shift of the band gap energy.

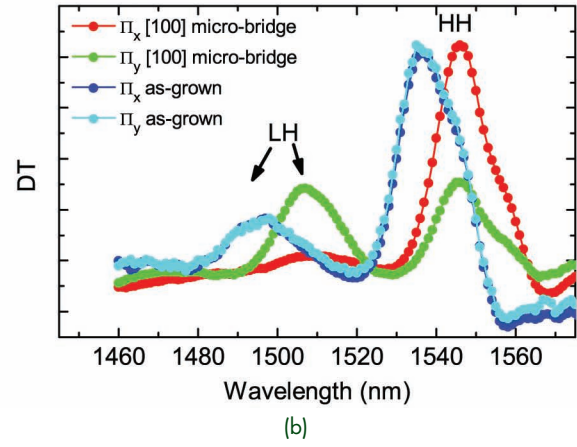
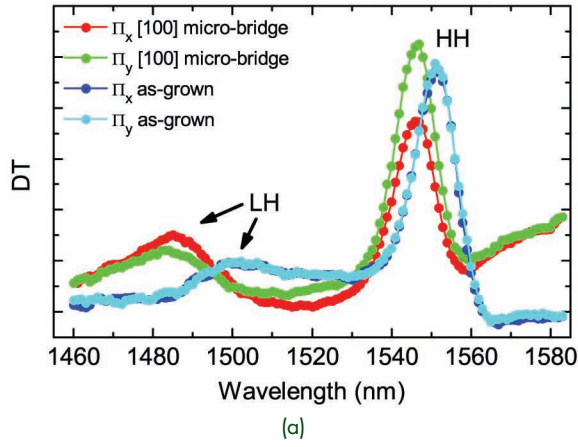


FIGURE 9
Band structure deformation and induced birefringence along a quantum well microbridge similar to that of Fig. 7(b). HH: heavy hole. LH: light hole. DT: differential transmission. Π_x : polarization parallel to the microbridge. Π_y : polarization orthogonal to the microbridge.